

ONR Postdoctoral Fellowship: Geoacoustic Inversion and Source Localization in a Randomly Fluctuating Shallow Water Environment

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Award Number: N00014-08-1-0204

LONG-TERM GOALS

The long-term goal of this project is to understand and mitigate the uncertainties of shallow-water acoustic inversions caused by strong oceanic temporal and spatial variability. To achieve this goal, we need to investigate the connection between acoustic signal fluctuations and the water-column variability, and further incorporate this connection into the acoustic inversions for increasing the inversion performance.

OBJECTIVES

The scientific objectives of this project are centered on improving acoustic inversions for estimating bottom properties and source position in a randomly fluctuating shallow-water ocean. The first objective is to develop and test a new data nullspace projection method to suppress the inversion errors caused by the random water-column fluctuations. This projection method will be applied onto existing geoacoustic inversion and source localization techniques. The acoustic and oceanographic data collected from the SW06 experiment [1], a multi-disciplinary experiment sponsored by the ONR and conducted on the Mid-Atlantic Bight continental shelf in 2006, are used to study how unaccounted-for water column variability negatively affects acoustic inversion results, and how these effects can be reduced by applying the projection method.

APPROACH

The data nullspace projection method is the key method developed and used in this project to reduce the inversion uncertainties caused by random water-column fluctuations. The core of this method is to project the acoustic signals used for inversions onto a data nullspace that does not connect to the oceanic variability. In this way, the acoustic signal variations due to the water-column fluctuations can be suppressed, and the desired information about bottom geoacoustic parameters and source location contained in the acoustic signals can be distinctly exposed. Empirical orthogonal function (EOF) analysis is also utilized in this method to determine a set of orthonormal basis functions, the EOF modes, for decomposing the fluctuating acoustic properties in the water column. The reason for doing this is that the data nullspace can be enlarged, so that more useful information contained in the acoustic signals can be captured. To determine the data nullspace, a water-column kernel that relates the acoustic signal variations with the oceanic EOF modes is first derived from linear perturbation theory, and then the data nullspace can be obtained by applying singular value decomposition onto the water-column kernel matrix.

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 30 SEP 2008		2. REPORT TYPE Annual		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE ONR Postdoctoral Fellowship: Geoacoustic Inversion And Source Localization In A Randomly Fluctuating Shallow Water Environment				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Woods Hole Oceanographic Institution, MS#11,Woods Hole,MA,02543				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES code 1 only					
14. ABSTRACT The long-term goal of this project is to understand and mitigate the uncertainties of shallow-water acoustic inversions caused by strong oceanic temporal and spatial variability. To achieve this goal, we need to investigate the connection between acoustic signal fluctuations and the water-column variability, and further incorporate this connection into the acoustic inversions for increasing the inversion performance.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 9	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

The SW06 experiment provides excellent acoustic and oceanographic data for studying shallow-water acoustics. The acoustic data include continuous-wave and broadband signals covering a frequency range from 50 Hz up to 1k Hz in the low frequency acoustics component of the experiment. The signals were transmitted from towed and moored sources and received by hydrophone arrays. The techniques developed in this project are tested and implemented using the experiment data. Also, the extensive oceanography measurements will be utilized to better estimate the temporal and spatial statistics of the oceanic variability.

WORK COMPLETED

The tasks completed this year are itemized below.

1. Development and improvement of the data nullspace projection method

A study has been done to show that the inversion result can be improved with the data nullspace projection to reach a better balance between the solution variance and resolution. In addition, an objective way is found to determine how many EOF modes should be used in the projection method so that we can greatly reduce the inversion uncertainties caused by the water-column fluctuations and yet maintain good inversion resolution.

2. Perturbative geoacoustic inversion with data nullspace projection

The acoustic data collected from the J-15 towed source experiment conducted by Dr. Kyle Becker (Appl. Res. Lab., Penn. State Univ.) in the SW06 experiment is being used in this project to invert for the bottom sound speed profile at the experiment site. The source, which transmitted continuous-wave tones at 50, 75, 125, and 175 Hz, was towed along radials toward and away from a vertical and horizontal hydrophone line array to create synthetic apertures. The horizontal wavenumbers of the propagating modes of the transmitted tones are estimated with a method briefed below. A vertical mode filter is first utilized for isolating the acoustic propagating modes, and then the horizontal wavenumbers of each mode along the source track can be estimated from the first derivative of the phase of mode filter outputs with respect to the source-to-receiver range. Note that the vertical mode functions used in the filter are calculated by the acoustic normal mode program KRAKEN [2] with the *in situ* water sound speed measurements on the vertical hydrophone line array and a bottom model provided by a previous study [3]. The resultant modal wavenumber estimates (shown in the Figure 1) are further averaged over the whole source track and used as the input data for the inversion.

EOF analysis is implemented on the *in situ* sound speeds measured on the vertical hydrophone line array. A set of dominative EOF modes is found to describe the water-column sound speed variations and to be used in the data nullspace projection method. Two perturbative geoacoustic inversions with and without the data nullspace projection are performed. In both inversions, the water-column sound speed profile in the environment background model is the average sound speed profile measured on the vertical hydrophone line array during the J-15 towed source experiment, and the model water depth is the average value of the true water depths along the source track, which mildly vary between 80 m and 83 m. Since the average sound speed profile at the receiver site is taken to represent the profiles along the source track, the environment background model has considerable water-column mismatch. As a result, the inversion without the projection can not converge due to the contamination from the water-column mismatch. The inversion with the projection, on the other hand, does converge, and the resultant bottom sound speed profile is shown in Figure 2, where one can see that a lower sound speed layer on the top of the sub-bottom section is resolved.

3. Bayesian geoacoustic inversion with data nullspace projection

A numerical simulation has been implemented to show the feasibility of using the data nullspace projection to improve Bayesian geoacoustic inversion. A linear internal wave model is used to generate a random internal wave field, and, after implementing EOF analysis, it is found that using three EOF modes is adequate to describe the random water-column fluctuations. A homogeneous bottom model is given in this test, which leads two bottom properties, sound speed and density, to be determined in the inversion procedure. A set of modal wavenumbers at four frequencies (50, 75, 125, and 175 Hz), complementary to the data collected in the J-15 towed source experiment of Dr. Kyle Becker, are calculated by the KRAKEN program. Without the data nullspace projection the inversion needs to determine five parameters; two of them are bottom parameters, and the rest are the water-column sound speed EOF coefficients. On the other hand, with the data nullspace projection only the two bottom parameters need to be determined. The inversion results are shown in the Figure 3, and one can see that the inversion with the data nullspace projection yields a maximum likelihood solution agreeing better with the given ground-truth.

4. Horizontal radiation of sound from the termination of an acoustic duct formed by nonlinear internal gravity waves

In addition to the inversion work, the horizontal radiation of sound from the termination of a truncated internal wave duct is studied. Since the radiation effect is one of the causes of acoustic signal variability seen in the data, it needs to be thoroughly investigated before we can develop an adequate scheme to reduce the inversion uncertainties caused by this effect.

The horizontal, modal trapping of sound in an internal wave duct leads to a rather complicated horizontal eigenvalue problem to solve, due to the detailed shapes of the internal waves that form the duct. Also, the sound radiation from a real, irregular duct termination is not simple to be handled by a theoretical means. So, rather than addressing a complicated case, a simple duct model which will still show most of the physics associated with the ducting and radiation effects is first considered. This model has two homogeneous water-column layers (the sound speed in the upper layer is slightly faster), and a homogeneous bottom is assumed. Medium absorption is neglected in both the water column and the bottom. Simplified internal waves with square waveforms and parallel wavefronts depress the water-column layer interface to a certain depth, and the acoustic duct formed by the waves abruptly terminates at some place where an open end is formed. A three-dimensional normal mode solution is found to describe the sound field in the duct, and then Huygens' Principle is adopted to calculate the radiation field. The result of a calculation example is shown in Figure 4, and the environment model settings are provided in the caption of the figure.

To handle a realistic environment, a computer code implementing a three-dimensional parabolic approximation in Cartesian coordinates [4] is employed. The result from a numerical simulation shows a radiation beam pattern with similar features suggested by the simplified analytic model described above.

RESULTS

The results drawn from the inversion work to date are summarized here. In theory, the data nullspace projection method utilizes the following two important properties of the EOF decomposition and the data nullspace.

1) Compactness of the EOF decomposition, which allows us to reduce the rank of the water column kernel matrix, so that the existence of the data nullspace is guaranteed, and its size will be large enough to expose most of the information about bottom geoacoustic parameters and source location contained in the acoustic data.

2) Orthogonality of the data nullspace to the column vectors of a kernel matrix, which allows us to suppress the acoustic data variations due to uncertain water-column fluctuations, so that the inversion results can be more accurate.

The result from the perturbative geoacoustic inversion using the modal wavenumber data shows that the data nullspace projection can take care of the unknown water-column mismatch in the environment background model. Without using the projection method, the inversion can not even converge. The simulation of Bayesian geoacoustic inversion also has promising result. With the data nullspace projection, the dimensions of the parameter space are reduced so that the inversion process speed can be improved, and more importantly a better solution is reached.

The conclusions drawn from the study of the horizontal radiation of sound from the termination of a truncated internal wave duct are summarized here. For an acoustic source located in such a duct and sufficiently far from the termination, some of the propagating sound may penetrate the internal wave “wall” at high grazing angles, but a fair amount of the sound energy is still trapped in the duct and propagates towards the termination. The across-duct sound energy distribution at the termination is unique for each acoustic vertical mode, and the sound radiating outward forms significant horizontal beams associated with individual vertical modes. From both the analytical expressions and numerical calculations we see complex horizontal interference patterns within the duct. Also, anomalous sound radiation fields, having mode-dependent patterns with strong azimuthal and temporal variability, are predicted at locations far from the termination of a truncated internal wave duct, even though there is no evidence of a ducting condition at those locations.

IMPACT/APPLICATIONS

The most important impact of this project is to increase the capability of underwater acoustic inversion and source localization techniques in a randomly fluctuating shallow-water ocean. Also, the data nullspace projection method developed in this project can in theory be applied to many sonar systems to reduce the effects of unavoidable environmental variability.

RELATED PROJECTS

This postdoctoral fellowship is under the supervision of Dr. James Lynch at Woods Hole Oceanographic Institution. The acoustic and oceanographic data used in this project are collected from the ONR sponsored SW06 experiment. The Investigators are also working with Dr. Timothy Duda to investigate the horizontal radiation of sound from the termination of an acoustic duct formed by nonlinear internal gravity waves.

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PUBLICATIONS

- Lin, Y.-T. and J. F. Lynch, A data nullspace projection method to reduce geoacoustic inversion uncertainties caused by water-column fluctuations, submitted to *J. Acoust. Soc. Am.*
- Duda, T. F., Y.-T. Lin and J. F. Lynch, Acoustic mode beam effects of nonlinear internal gravity waves in shallow water (A), *J. Acoust. Soc. Am.*, 123, 3943 (2008). [published, non-refereed]
- Lynch, J. F., Y.-T. Lin and A. Newhall, Applying the Data Nullspace Projection Method to a Geoacoustic Bayesian Inversion in a Randomly Fluctuating Shallow-Water Ocean (A), *J. Acoust. Soc. Am.*, 123, 3589 (2008). [published, non-refereed]
- Duda, T. F., J. F. Lynch, Y.-T. Lin, A. Newhall, H. Graber and M. Caruso, The effects of non-linear internal wave curvature on acoustic propagation (A), *J. Acoust. Soc. Am.*, 123, 3588 (2008) [published, non-refereed]

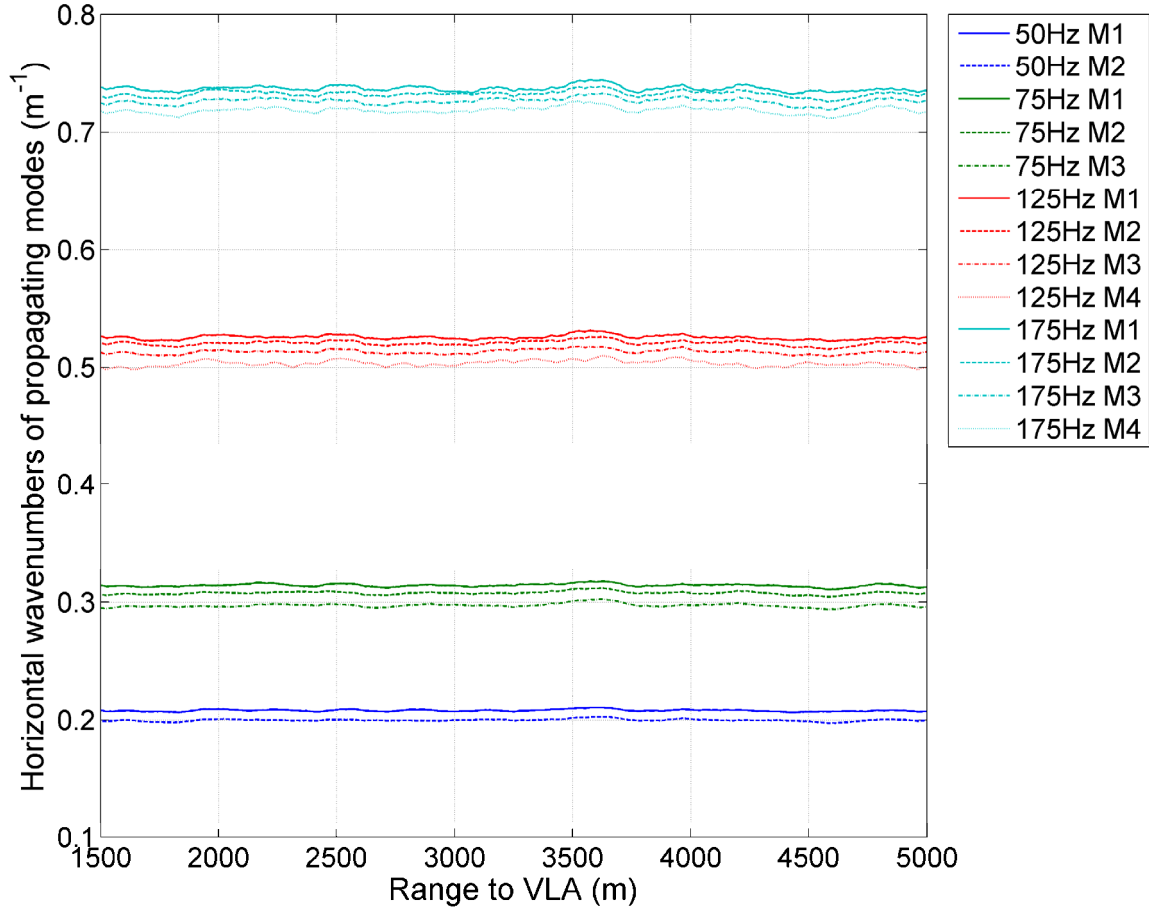


Figure 1. Modal wavenumbers estimates over the source track in the J-15 towed experiment
[Modal wavenumbers at four frequencies (50, 75, 125 and 175 Hz) are measured from the continuous-wave tones transmitted by a towed source and received at a vertical hydrophone line array. Total 13 modes are analyzed; 2 modes at 50 Hz, 3 modes at 75 Hz, 4 modes at 125 Hz and 4 modes at 175 Hz. The variability seen in the data is caused by the environment complexity, including the spatially varying sediment properties and the spatial and temporal water-column fluctuations.]

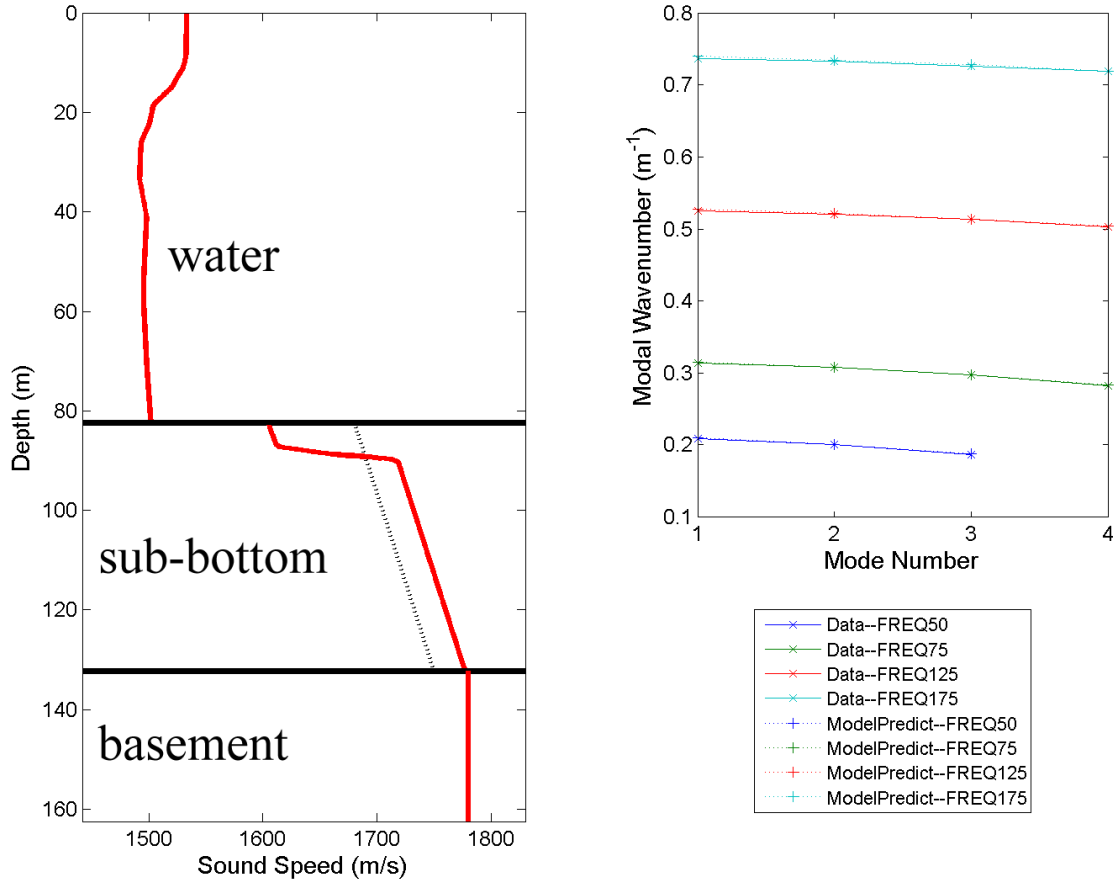


Figure 2. Inverted range-average bottom sound speed profile (left panel) at the J-15 towed source experiment site and the modal wavenumber data fitness (right panel)

[The water-column sound speed profile plotted here is the average profile measured on the vertical hydrophone line array during the experiment. The black dashed line shown in the sub-bottom section is the initial guess in the perturbative inversion procedure. One can see that a lower sound speed layer on the top of the sub-bottom section is resolved, and with the inverted bottom model the modal wavenumber predictions agree with the measured data very well.]

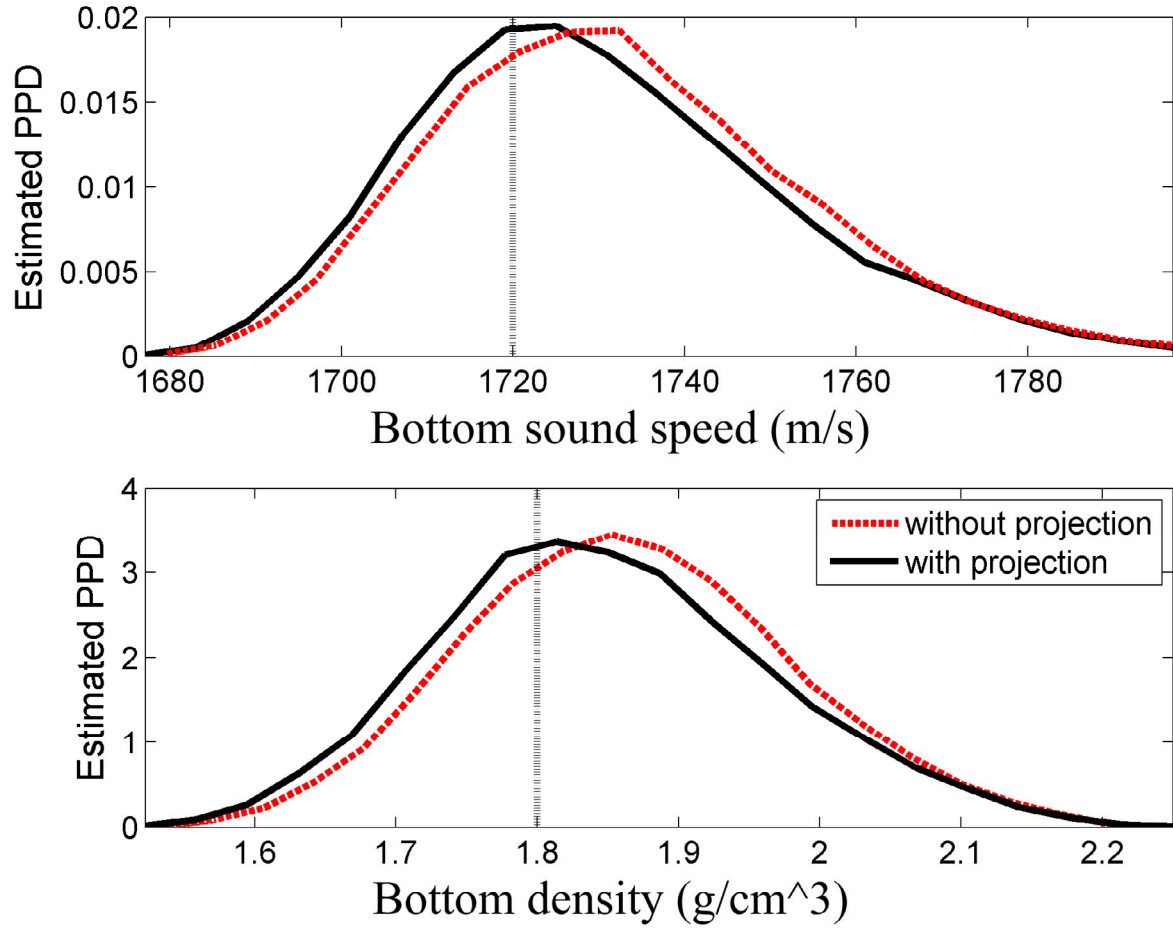
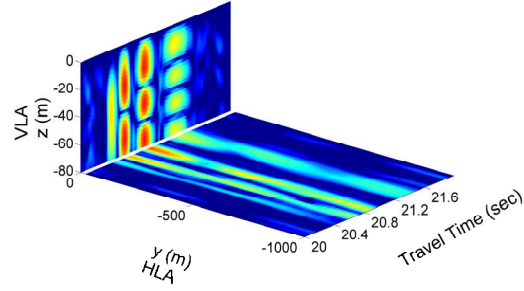
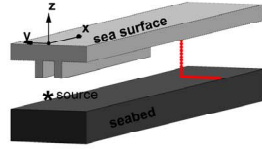


Figure 3. Numerical simulation results of Bayesian geoacoustic inversion in the presence of linear internal waves

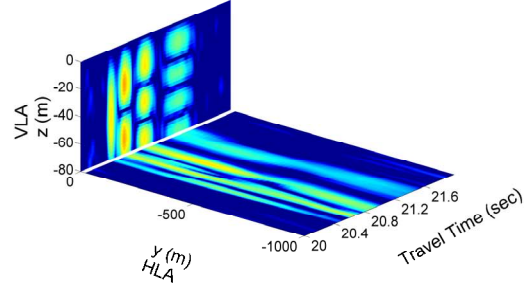
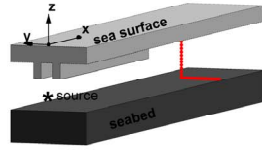
[The vertical lines indicate the true sound speed and density in the homogeneous bottom. The simulation results suggest that the inversion with the data nullspace projection yields a maximum likelihood solution agreeing better with the given ground-truth.]

Broadband Source
(central freq. 100Hz, bandwidth 25Hz) VLA at (x=30.0km, y=0.0m), 1000.0m HLA along y axis

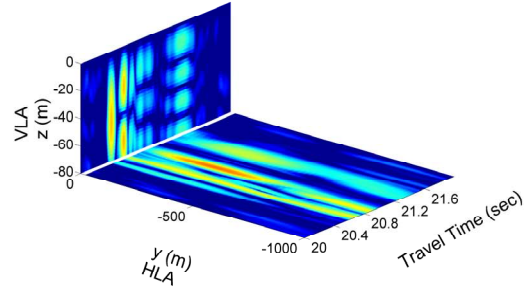
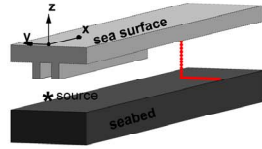
Middle of the duct at $y = 0.0\text{m}$



Middle of the duct at $y = 45.0\text{m}$



Middle of the duct at $y = 75.0\text{m}$



Middle of the duct at $y = 130.0\text{m}$

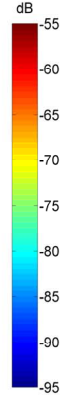
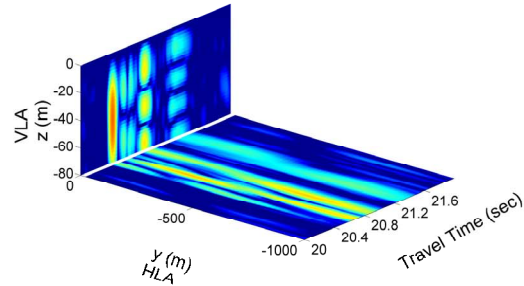
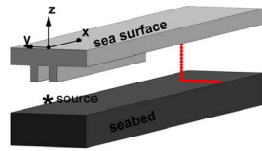


Figure 4. Analytical model of broadband sound radiation from the termination of a truncated internal wave duct

[The right panels illustrate the pulses received at a vertical and horizontal hydrophone line array, denoting by the red lines in the left panels, when the internal wave duct locates at four different positions. The broadband pulse is centered at 100 Hz with a 25 Hz bandwidth, and the environment model settings are detailed below. The sound speeds in the upper and lower water layers are 1,520 m/s and 1,480 m/s, respectively. The density in the water column (in both layers) is 1 g/cm^3 . The water depth is 80 m, and the thickness of the upper water layer is 20 m. The amplitudes of the two internal square waves forming the acoustic duct are both 20 m, and their wavelengths are both 200 m. The gap between the internal waves is 300 m wide, and the internal waves abruptly terminate at $x = 20\text{ km}$. The sound speed and density in the homogeneous bottom are 1,700 m/s and 1.5 g/cm^3 .]